Design Science Methodology

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Motivation

• Computing Sciences
  – Information Systems, Software engineering, Artificial Intelligence, Human-Computer Interaction, etc.

• Computing sciences have evolved into disciplines with both
  – a design component and
  – an empirical research component

• Research methodology must be properly aligned with this Design Science research methodology
Methodology across knowledge disciplines

• Do these disciplines have the same methodology?
  – Technical science?
  – Social science?
  – Physical science?
  – Mathematics?

• Do they appreciate each other’s methodology?
  – For social scientists, engineers are tinkerers with low social status
  – For technical scientists, social scientists are chatterboxes
  – For physicists, statistics is stamp collecting
  – The mathematicians provide the foundations of civilization, the others just don’t understand it.
Our approach

• All research is problem-solving
  – Checklists for the design cycle and the empirical cycle
• Empirical research updates theories
• Designers use theories to predict the effect of their designs in a context

• Wieringa, R.J. (2014) Design science methodology for information systems and software engineering. Springer Verlag
Outline

1. What is design science
2. Research goals and problems
3. The design and engineering cycles
4. Theories
   – Conceptual frameworks
   – Generalizations
5. Empirical cycle
6. Scientific inference
Outline

1. What is design science
2. Research goals and problems
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• Design science is the design and investigation of artifacts in context
Reality check

• What research problems are you investigating?

• Design of conceptual /physical/software/social structures
Research problems in design science

To design an artifact to improve a problem context

- Design software to estimate Direction of Arrival of plane waves, to be used in satellite TV receivers in cars
- Design a MARP system to be used for aircraft taxi planning
- Design a data location regulation auditing method
- Design a usability and usefulness test with consultants as subjects.

Problems & Artifacts to investigate

To answer knowledge questions about the artifact in context

- “Is the DoA estimation accurate enough in this context?”
- Is it fast enough?
- “Is this agent routing algorithm deadlock-free in this context?”
- How much delay does it produce?
- Is the method usable and useful for consultants?
- What does this test teach me about usability?
Framework for design science

**Social context:**
Location of stakeholders

- **Source of relevance.**
- **Relevance, and money, comes and goes**

**Goals, budgets**

**Designs**

**Design science**

**Improvement design**

- Existing problem-solving knowledge, Old designs
- New problem-solving knowledge, New designs

**Answering knowledge questions**

- Existing answers to knowledge questions
- New answers to knowledge questions

**Knowledge context:**
- Mathematics, social science, natural science, design science, design specifications, useful facts, practical knowledge, common sense, other beliefs

- **Source and destination of theories**
- **Theories are forever**
(Dis)similarity to Hevner et al. framework

Social context:
- Location of stakeholders

Knowledge context:
- Mathematics, social science, natural science, design science, design specifications, useful facts, practical knowledge, common sense, other beliefs

Relevance cycle
- Hevner et al. want to identify these two activities
- But the methodology of these two activities is totally different
Discussion

• Who are the stakeholders of your projects?
• Do they know about this?
• Who pays for the project?
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2. Research Goals and Problems
Goal structure

Social context

To achieve stakeholder goals: Utility (sponsor), fun (designer), curiosity (empirical researcher)

To improve a problem context

Contribution

Design research

To (re)design an artifact

To (re)design a research instrument

Contribution

To answer knowledge questions

Three kinds of design research questions

• Design problems (a.k.a. technical research questions)
  – Design <artifact> to satisfy <requirements> in order to improve <problem context> with respect to <stakeholder goals>

• Knowledge questions
  – Empirical research questions
    • Descriptive: What happened? When? Where? Who was involved?
    • Explanatory: Why?
  – Analytical research questions (math, conceptual, logical)
Reality check

• Please give examples of research questions that do not fit one of these formats.
Template for design problems

- Improve <problem context>
- by <treating it with a (re)designed artifact>
- such that <artifact requirements>
- in order to <stakeholder goals>

- *Reduce my headache*
- *by taking a medicine*
- *that reduces pain fast and is safe*
- *in order for me to get back to work*
Template for design problems

- Improve <problem context>
- by <treating it with a (re)designed artifact>
- such that <artifact requirements>
- in order to <stakeholder goals>

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Problem context and stakeholder goals.
Stakeholder language
Template for design problems

- Improve <problem context>
- by <treating it with a (re)designed artifact>
- such that <artifact requirements>
- in order to <stakeholder goals>

- Reduce my headache
  - by taking a medicine
  - that reduces pain fast and is safe
  - in order for me to get back to work

Artifact and its desired properties.
Technical language
Descriptive and explanatory knowledge questions

• Descriptive questions:
  – What happened?
  – When?
  – Where?
  – What components were involved?
  – Who was involved?
  – etc.

• Explanatory questions:
  – Why?
    1. What has *caused* the phenomena?
    2. Which *mechanisms* produced the phenomena?
    3. For what *reasons* did people do this?
• **Descriptive question: What is the performance of this program?**
  – Execution time for different classes of inputs
  – Memory usage
  – Accuracy
  – Etc. etc.

• **Explanatory question: Why does this program have this performance?**
  1. **Cause:** because it received this input (and not another input)
  2. **Mechanism:** because it has this architecture with these components
  3. **Reasons:** Because users use it only for a few simple tasks
What about prediction questions?

• A prediction question is not a research problem!
  – We cannot observe the future

• To solve a prediction problem, we need a theory
  – The theory is built by answering descriptive and explanatory knowledge questions
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Activities in design science

Improvement design

Engineering cycle

Problems to be investigated, artifacts to be investigated

Answering knowledge questions

Research cycle

Knowledge
Implementation evaluation = Problem investigation

- Stakeholders? Goals?
- Conceptual problem framework?
- Phenomena? Causes, mechanisms, reasons?
- Effects? Positive/negative goal contribution?

Treatment validation

- Context & Artifact → Effects?
- Effects satisfy Requirements?
- Trade-offs for different artifacts?
- Sensitivity for different Contexts?

Treatment design

- Specify requirements!
- Requirements contribute to goals?
- Available treatments?
- Design new ones!
• **Treatment** consist of introducing an artifact in the problem context
  – Treatment design = artifact design

• **Implementation** = Introduction of the treatment in the intended problem context

• We consider the case where the intended problem context is the social world, the location of stakeholders
  – So in this course implementation = transfer to the stakeholder context = technology transfer
Validation versus evaluation

• **To validate** a design is to *predict* the effects of an implementation of the design, and the utility with respect to stakeholder goals.

• **To evaluate** an implementation is to investigate the effects of an implementation *that have occurred* and their utility with respect to stakeholder goals
Design research projects iterate one or more times through the design cycle.

**Design cycle**

This lists all your design research knowledge questions.

**Implementation evaluation** = 
**Problem investigation**

- Stakeholders? Goals?
- Conceptual problem framework?
- Phenomena? Causes, mechanisms, reasons?
- Effects? Positive/negative goal contribution?

**Treatment validation**

- Context & Artifact → Effects?
- Effects satisfy Requirements?
- Trade-offs for different artifacts?
- Sensitivity for different Contexts?

**Treatment design**

- Specify requirements!
- Requirements contribute to goals?
- Available treatments?
- Design new ones!
This lists all your design research knowledge questions. With which research designs can we answer them?
## Research designs

<table>
<thead>
<tr>
<th></th>
<th>Observational study (no treatment)</th>
<th>Experimental study (treatment)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Case-based:</strong></td>
<td>Observational case study</td>
<td>• Expert opinion,</td>
</tr>
<tr>
<td>investigate</td>
<td></td>
<td>• Mechanism experiments,</td>
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<td>single cases</td>
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<td>• Technical action research</td>
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<td>look at</td>
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<td>and mechanisms</td>
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| **Sample-based:** | Survey                           | • Statistical difference-     |
| investigate       |                                  | making experiment             |
| samples drawn     |                                  |                                |
| from a population |                                  |                                |
| look at           |                                  |                                |
| averages and      |                                  |                                |
| variation         |                                  |                                |

* e.g. simulations
* e.g. pilot project

**Treatment group-control group designs**
Research designs in evaluation and problem investigation

Implementation evaluation = Problem investigation

- Stakeholders? Goals?
- Conceptual problem framework?
- Phenomena? Causes, mechanisms, reasons?
- Effects? Positive/negative goal contribution?

Possible research designs:
- Observational case study, *e.g. study some social network mechanisms in a global SE project*
- Survey: *e.g. survey of the use of UML in SW companies in Brazil*
- Single-case mechanism experiment: *e.g. send messages through a company network to evaluate its performance*
- Statistical difference-making experiment: *e.g. compare two implemented techniques in two groups of professionals*
Design cycle

Implementation evaluation = Problem investigation

Treatment validation

- Context & Artifact → Effects?
- Effects satisfy Requirements?
- Trade-offs for different artifacts?
- Sensitivity for different Contexts?

Design cycle

- Expert opinion, *e.g.* focus group
- Single-case mechanism experiment: *test a prototype of an algorithm in simulated environment; test a prototype of a method in a classroom on students.*
- Statistical difference-making experiment: *compare two proposed techniques in two groups of students.*
More robust generalizations

Population

Large samples

Small samples

Idealized

Practical

More realistic conditions of practice

Laboratory credibility

Scaling up to conditions of practice

Street credibility
• Scaling up:
  – Single-case mechanism experiment (lab simulation)
  – Expert opinion
  – Single-case mechanism experiment (field simulation)
  – TAR (apply technique in a consultancy project)
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• A **theory** is a belief that there is a pattern in phenomena.
  – Speculations: “*The NSA is monitoring all my email*”
  – Idealizations: “*Merging two faculties reduces cost in theory, not in practice.*”
  – Opinions: “*The Dutch lost the competition because they are not a team.*”
  – Wishful thinking: “*My technique works better than the others.*”
  – Scientific theories: *Theory of electromagnetism*
Scientific theories

• A **scientific** theory is a belief that there is a pattern in phenomena, that
  – Has survived tests against experience
    • Observation, measurement
    • Possibly: experiment, simulation, trials
  – Has survived criticism by critical peers
    • Anonymous peer review
    • Publication
    • Replication

• Examples
  – *Theory of electromagnetism*
  – *Theory of cognitive dissonance*
  – *The Balance theorem in social networks*
  – *Theories X, Y, Z, and W of (project) management*
  – *Technology Acceptance Model*
Theories are fallible

• Fallibilism: All theories may be wrong!
  – Outside mathematics there is no certainty
  – And even there, mathematicians make mistakes (Lakatos’ *Proofs and Refutations*)

• In other words, all theories are improvable
Falsificationism

• Introduced by the philosopher Karl Popper
  – Mechanical version: If the prediction of a theory is contradicted by observation, then reject the theory.
  – Sophisticated version: If the prediction of a theory is contradicted by observation, then
    • try to replicate it,
    • try to understand it,
    • try to improve the theory so that it can deal with the observation,
    • publish whatever comes out of this.
The structure of scientific theories

1. Conceptual framework
   – Definitions of concepts.

2. Generalizations
   – Express beliefs about patterns in phenomena.
Theory of electromagnetism

• Conceptual framework:
  – Definitions of electric current, electric charge, potential difference, electric resistance, electric power, capacitance, electric field, magnetic field, magnetic flux density, inductance, ..., ... and their units.

• Generalizations
  – Electric charges attract or repel one another with a force inversely proportional to the square of their distance.
  – Magnetic attract or repel one another in a similar way and always come in north-South pairs.
  – An electric current inside a wire creates a corresponding circular magnetic field outside the wire.
  – A current is induced in a loop of wire when it is moved towards or away from a magnetic field.
Theory of cognitive dissonance

• Conceptual framework
  – Cognitive dissonance is the mental stress experienced by an individual who holds contradictory beliefs or values, or is confronted by new information that conflicts with existing beliefs or values

• Generalization
  – People engage in dissonance reduction to bring their beliefs and actions in line with one another four ways:
    • Change behavior to agree with belief (‘eat less chocolate’)
    • Change belief to justify behavior (‘occasional chocolate eating is OK’)
    • Add new intention or behavior (‘I’ll work out tomorrow’)
    • Deny information that conflicts with existing beliefs (‘this is low-fat chocolate’)

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The Balance Theorem in social networks

• Conceptual framework
  – Definition of concepts of graph, link, friend/enemy, complete graph (each pair of nodes connected), balanced graph (no --- or ++- triangles)

• Generalization
  – Large call networks are almost balanced (V.D. Blondel, A. Decuyper and G. Krings - “A survey of results on mobile phone datasets analysis”)
  – Mathematical theorem: If a labeled complete graph is balanced, then
    • either all pairs of nodes are friends,
    • or else the nodes can be divided into two groups, X and Y, such that every pair of nodes in X like each other, every pair of nodes in Y like each other, and everyone in X is the enemy of everyone in Y.

• Idealizing assumptions may allow us to understand real-world phenomena
Technology Acceptance Model

• Conceptual framework
  – Definitions of perceived usefulness, perceived ease of use, perceived resources, attitude towards using, behavior intention to use, actual system use

• Generalization

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• A **conceptual framework** consists of definitions of concepts, often called **constructs**.

• **Variables, relations among variables**

• **Populations, probability distribution of variable**

• **Entities, attributes, relations, taxonomy, cardinality, ...**

• **Events, actions, processes, procedures, constraints, ...**
• We can define two kinds of conceptual structures

1. **Architectural structures**: Class of physical/social/technical systems, architecture, components with capabilities, interactions

2. **Statistical structures**: Population, variables with probability distributions, relations among variables
Architectural structures

- The world is structured as a collection of systems
  - Social, physical, technical, psychological, biological, ...
  - Each system has **components** with **capabilities and limitations** of behavior
  - that can **interact** with each other in specific ways.
• Glennan - "Mechanisms and the nature of causation". 1996
• Glennan - "Mechanisms and the nature of causation". 1996

A voltage switch
• Bechtel & Abrahamsen – "Explanation; a mechanistic alternative." 2005
Bechtel & Abrahamsen – “Explanation; a mechanistic alternative.” 2005
Mechanisms in sociology

• The balance theorem
• Tipping point in an economy with network effects
• Clustering mechanisms in like/dislike networks
• ...

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Cognitive mechanism of program comprehension
Theory of cognitive dissonance

• **Conceptual framework**
  – *Class of systems: people interacting with the real world*
  – *Components: beliefs, intentions, values, facts, observations, conflict between facts and observations*
  – *Capabilities of people:*
    • *Change behavior*
    • *Change a value*
    • *Change intention*
    • *Deny observation*
    • *Deny fact*
• Conceptual framework provides a way to describe phenomena (a frame)
• but does not itself provide generalizations about phenomena
  – They cannot be falsified!
  – They can be useful, i.e. contribute to a purpose
Other examples

• In all of these examples we recognize in each case/population element an architecture consisting of components that have capabilities to interact.
  – Theory of electromagnetism
  – The Balance theorem in social networks
  – Technology Acceptance Model
  – Theories X, Y, Z, and W of (project) management
More examples

• Examples
  – *A software prototype in a simulated context*
  – *Software engineering projects in the real world*
  – *Information systems in organizations*
  – *Risk assessment methods for IT security*
  – *Business networks*

• Which architecture to recognize in a case? That depends on which generalizations we would like to be able to draw.
Advantages of architectural structures

Architectures can be used to decompose complex problems into simpler problems

- Study one component at a time;
- Study a system architecture while abstracting from internal structure of components

This in turn can be used for

- **Explanation, diagnosis, debugging**: Trace system-level phenomena to component properties.
- **Prediction, design**: Explore the effects of putting different components together.
- **Generalization**: Reason about similarity of cases or populations.
Statistical structures

• The world is structured as a population.
  – A population is set of all objects that satisfy a predicate, called the population predicate.
  – Internal structure of population elements is ignored.
  – A (random) variable is an observable property of population elements
  – A probability distribution of a variable X is a mathematical function that summarizes the probability of randomly selecting a value of X from the population

• (``Random’’ means: No systematic selection proces. Internal structure of the selection process does not provide information about the outcome of the selection.)
Population

- **Population** is set of all objects that satisfy a predicate, called the *population predicate*.
  - *All software prototypes in a simulated context, similar to a particular prototype & context*
  - *All agile software engineering projects in the real world*
  - *All ERP systems in large organizations*
  - *All risk assessment methods for IT security*
  - *All business networks*

- The population predicate is a *similarity predicate*
  - When defining a population predicate, we *do* often consider internal structure of population elements.
Variables

• A **random variable** is an observable property of population elements

• **X-box** is the multiset of values of X on a population
  – *Weight of people, effort of SE projects, numbers on football shirts.*
Statistical reasoning is about boxes

- **XY-box** is the multiset of pairs of values of \((X, Y)\) on a population, etc.
  - *Execution time of implementations, accuracy of output, effort spent on a project, duration of a project, (effort, duration) of a project, etc.*

- In a population,
  - Each variable has properties of variation (average, variance)
  - And sets of two or more variables have relationships of covariation
Probability distributions

• **Probability distribution** of $X$ is a mathematical function that summarizes the probability of selecting a sample of values in a random draw from the population.
Chance models

• **Chance model** of $X$:
  1. Definition of the meaning of numbers in the $X$-box
  2. Assumptions about probability distribution of $X$
  3. Measurement procedure
  4. Sampling procedure
Example

- Population of open source web applications
- Random variable ImpV indicates implementation vulnerabilities.
- Chance model of ImpV:
  1. Definition: The numbers on the tickets in the ImpV-box are proportions of implementation vulnerabilities among total number of vulnerabilities in a web application. (pages 564-565)
  2. Assumptions: binomial distribution. I.e. the proportions of implementation vulnerabilities in different web applications are independent, and the probability that a vulnerability is an implementation vulnerability, is constant across all web applications
  4. Sampling procedure: Not specified. 20 applications are listed.
Advantages of statistical structures

• Statistical structures can be used to make large-scale population properties visible
  – Even when an individual shows no regularities

This in turn can be used to

• Describe aggregate phenomena in a sample
• Generalize from a sample to a population (sample-based)
  – Estimate patterns in the population not visible at the individual level (e.g. identify needs in a population)
  – Estimate the effect of treatments in the population (prediction of policy impact)
• Useful for policy-makers
Hybrid structures

• Statistical study within a case
  1. Case study of a large global SE project: e.g. an architectural study of roles and interactions among software engineers;
  2. Contains a statistical study of the population of software engineers in this project.

• Case study of a population element
  1. Statistical survey of a sample of projects:
  2. Followed by case studies of a few projects, in order to understand mechanisms responsible statistical results.
If the studied phenomena contain people ...

they too have conceptual frameworks
Sharing and interpreting a conceptual framework

• Concepts shared by people in the domain may be adopted by researchers that investigate the domain
  – *Goal, requirement, effort, etc.*
  – Adopting these concepts in the conceptual research framework may allow additional understanding

• Concepts defined by researchers may be adopted by people in the domain
  – *(software) object program structure, agile, etc.*
  – Adopting these concepts in the domain may allow definition of additional options for action

• Concepts may even make a round trip from domain to researchers to domain
Validity of a conceptual framework

• Conceptual framework cannot be true or false
  – A definition cannot be true or false
• It is a tool
  – People may be able to use it (usability)
  – ... for a useful purpose (utility)
• *E.g. the different definitions of “goal”, “requirement”, “specification”, design”.*
• “A goal is the space between two trees”
• **Construct validity** is the degree to which the application of constructs to phenomena is warranted with respect to the research goals and questions.

• ``Construct validity is the degree to which a test measures what it claims, or purports, to be measuring."

• ``Construct validity refers to the degree to which inferences can legitimately be made from the operationalizations in your study to the theoretical constructs on which those operationalizations were based."


Threats to construct validity

• Inadequate definition
  – No identification and classification criterion.
  – *E.g. “agile projects” without instruction how to recognize and count agile projects*

• Construct confounding
  – Our cases/sample may be cases/samples from more than one population. Then what is the target of generalization?
  – *Measuring the effect of an SE method in a sample of students.*
    • *Is this a sample of novice software engineers? Well educated software engineers? Captive software engineers?*
Operationalizations

- Some constructs cannot be measured
- **Operationalize** them:
  - Define them in terms of one or more indicators that *can* be measured
  - An **indicator** is a variable that can be measured
  - In software engineering, often called a *metric*. 
Threats to validity of operationalizations

• **Mono-operation bias**
  – Defining only one indicator for a construct
  – *E.g. measuring maintainability by effort to repair a bug only (and ignoring effort to find a bug or to test the repair).*

• **Mono-method bias**
  – Indicator measured in only one way.
  – *E.g. measuring effort to repair by questionnaires only*
Construct Validity, again

• **Construct validity** is the degree to which the application of constructs to phenomena is warranted with respect to the research goals and questions

• ``Construct validity is the degree to which a test measures what it claims, or purports, to be measuring.”
  – The paradox of analysis: if a vague concept is operationalized, either the operationalization is wrong or the concept is redefined

• ``Construct validity refers to the degree to which inferences can legitimately be made from the operationalizations in your study to the theoretical constructs on which those operationalizations were based.”
  – Indicators do not *causally influence* constructs
  – Paradox of analysis: construct validity is either 0 or 100%
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Target (scope) of generalization

• In case-based reasoning: defined by similarity predicate
  – Agile projects: Projects following one of the recognized agile methods such as Scrum or XP. How crisp is this?

• In sample-based reasoning: Defined by similarity predicate too!
  – Population predicate
    • Generalize, from sample of study population of agile projects, to the study population
  – Similar populations
    • Generalize from study population of agile projects to the theoretical population of all agile projects.
The structure of design generalizations

- (Artifact specification) X (Context assumptions) → Effects
  - (UML) X (SE project) → (Less errors)
  - (Cross-functional teams) X (Global SE project) → (Less errors)
  - (Algorithm) X (Context of use) → (Faster execution)

- Effects satisfy a requirement to some extent
  - Often, researchers have no clear requirements
  - Requirements come from stakeholder goals, so the relevance of a generalization depends on stakeholder goals
Discussion

• Do you recognize this?
• More examples ...
Why do we need theories?

- With a conceptual framework we can:
  - **Frame** a problem or artifact: *choose which concepts to use*
  - **Analyze** conceptual problem structure: *analyze the framework*
  - **Describe** a problem or artifact
  - **Generalize** about problem or artifact

- With a generalization we can
  - **Explain** phenomena
  - **Predict** phenomena
Examples

• Theories:
  – Theory of cognitive dissonance
  – Theory of electromagnetism
  – The Balance theorem in social networks
  – Theories X, Y, Z, and W of (project) management
  – Technology Acceptance Model

• What can we do with these theories:
  – Frame a problem or artifact
  – Analyze conceptual problem structure
  – Describe a problem or artifact
  – Generalize about problem or artifact
  – Explain phenomena
  – Predict phenomena
Explanations

• An explanation is hypothesis about how a phenomenon came about.
  – Causal explanations explain the occurrence of an event by the occurrence of an earlier event
  – Architectural explanations explain the existence of a causal relationship by the mechanisms that produced it
  – Rational explanations explain the behavior of actors by their goals.

• E.g. why is the light on?
Causal explanations

• Causal explanations say that an earlier event **made a difference** to a current event.
  – *Explanation of lower programming effort: Programming effort is lower because* we switched to UML
    • The earlier switch to UML resulted in the current reduction of programming effort
    • If we had not switched to UML earlier, our current programming effort would have been higher, other things being equal.

• Causality is difference-making.
  – It is unobservable.
  – It may be nondeterministic
Architectural explanations

- **Architectural explanations** explain the existence of a causal relationship by the mechanisms that produced it.
  - *Explanation why UML leads to lower programming effort:*
    - UML models resemble the domain more than other kinds of models;
    - they are easier to understand for software engineers;
    - They allow seamless transition from domain models to software models.

- A **mechanism** is the collection of interactions among components (entities, actors) that produces a response from a stimulus.
  - Mechanisms may be social, psychological, physical, technical, ...
  - Mechanisms can be observed; capabilities are unobservable
  - Mechanisms may be nondeterministic
Rational explanations

• **Rational explanations** explain the behavior of actors by their goals.
  
  – *Why do we have lower programming effort? Because we bid for fixed price contracts. We need to be sure that our software engineers work as efficiently as possible*

• Architectural explanation for social systems that include rational actors
  
  – We assume rationality in users, programmers, attackers, fraudsters, thieves, politicians, ... but their goals may not be our goals.
Predictions

• Explanations say how the present is an outcome of the past.
• Predictions look at the present and estimate what the future will be.

Some explanations are too incomplete to be used as predictions
  – *Explanations of the outcome of a football match*

Some predictions are descriptive, and do not provide an explanation
  – *In CMM 3 organizations developing embedded software, defect removal effectiveness is 98%.*

Some explanations can be used for prediction too
  – *Most examples of explanations given so far.*
The use of theories in design

Implementation evaluation = Problem investigation

- Stakeholders? Goals?
- Conceptual problem framework?
- Phenomena? Explanations?
- Effects? Contribution to Goals?

Treatment implementation

Explanations & predications needed

Treatment validation

- Context & Artifact → Effects?
- Effects satisfy Requirements?
- Trade-offs for different artifacts?
- Sensitivity for different Contexts?

Treatment design

- Specify requirements!
- Requirements contribute to goals?
- Available treatments?
- Design new ones!
Usability of design theories

• When is a design theory usable by a practitioner?
  (Context assumptions) X (Artifact design) \( \rightarrow \) Effects
  1. He/she is capable to recognize Context Assumptions
  2. and to acquire/build Artifact,
  3. effects will indeed occur, and
  4. will contribute to stakeholder goals/satisfy requirements

• Practitioner has to assess the risk that each of these fails
Example

- $(UML) \times (\text{any SE project}) \rightarrow \text{lower programming effort}$

- You are a practitioner.
  1. Can you recognize Context Assumptions?
  2. Can you acquire UML?
  3. Are you sure the effects will occur?
  4. Do they contribute to stakeholder goals?
Discussion

• Gregor’s view of theories.
  – My book page 103.
Outline

1. What is design science
2. Research goals and problems
3. The design and engineering cycles
4. Theories
   – Conceptual frameworks
   – Generalizations
5. Empirical cycle
6. Scientific inference
Checklist for the empirical cycle: context

1. Improvement goal?
2. Knowledge goal?
3. Current knowledge?
4. ...
5. ...
6. ...
7. Contribution to knowledge goal?
8. Contribution to improvement goal?

Design cycle
(slide 22)

Empirical cycle

Designing something useful

Answering a knowledge question

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Research problem analysis
4. Conceptual framework?
5. Research questions?
6. Population?

Data analysis
12. Data?
13. Observations?
14. Explanations?
15. Generalizations?
16. Answers?

Research execution
11. What happened?

Empirical cycle

Design validation
7. Object of study justification?
8. Treatment specification justification?
9. Measurement specification justification?
10. Inference justification?

Research & inference design
7. Object of study?
8. Treatment specification?
9. Measurement specification?
10. Inference?

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Research setup

- Researcher
- Treatment instrument
- Measurement instrument
- Object of Study
- Sample
- Representation
- Population
• In sample-based studies, ‘`representation’’ is achieved random sampling
  – A random sample may be **dissimilar** to any other sample from the same population.
  – No analogic reasoning from random sample to population
  – Randomness guarantees long-run stability of statistical properties

• In case-based research, OoS’s are studied sequentially

• In observational studies there is no treatment
  – But all instruments interact with the OoS’s.

• Which inferences you can do, depends on the research setup
Examples

• What is the population, the sample of objects of study, the measurements, and the treatments (if any)?
  – *Experiment with students to test a new SE technique to see if it leads to less programming effort*
  – *Survey of the use of UML in Brazil*
  – *Case study of IS implementation failure*
  – *Experimental use of a new effort estimation technique in a pilot project to see if it is more accurate*
## Kinds of empirical research methods

<table>
<thead>
<tr>
<th>Case-based: investigate single cases, look at architecture and mechanisms</th>
<th>Observational study (no treatment)</th>
<th>Experimental study (treatment)</th>
</tr>
</thead>
</table>
| | Observational case study | • Expert opinion  
| | | • Case-based mechanism experiments  
| | | • Technical action research  
| Sample-based: investigate samples drawn from a population, look at averages and variation | Survey | • Statistical difference-making experiment |
Example observational case study

An Empirical Study of the Complex Relationships between Requirements Engineering Processes and Other Processes that Lead to Payoffs in Productivity, Quality, and Risk Management

Daniela Damian and James Chisan
TSE 32(7) July 2006
Research design

- **Research context**
  1. **Improvement goal:** None. Curiosity-driven research.
  2. **Knowledge goal:** Fill gap between claims about RE and RE practice
  3. **Current knowledge:** A few published surveys, no case studies.
Research design

• Research problem analysis

4. Conceptual framework: definitions of requirements, productivity, quality, risk

5. Research questions:

– How do improvements in RE processes relate to improvements in productivity, quality, and risk management?

  1. How do improvements in the RE practice impact the early stages of development?

  2. How do they impact the downstream development stages?

  3. Which components of the RE process were more significant in contributing to this impact?

  4. How could the interaction between REP and other processes have contributed to these results?

6. Population: RE processes in software development organizations
Research design

• Research & inference design

7. Object of study: Introduction of RE at the Australian Center for Unisys Software

8. Treatment specification: No treatment. Observational research.


10. Inference: after the break!
Example Technical Action Research (TAR) study

What is TAR?

• Using an experimental technique
  – to help a client and → Helping a client
  – to learn about its effects in practice. → Experimenting with a technique
TAR methodology

**Researcher’s design cycle:**
Design a new technique

**Researcher’s empirical cycle:**
Validate a new technique

**Client’s engineering cycle:**
Solve a problem
TAR methodology

**Researcher’s design cycle:**
- Investigate problem
- Design treatment
- Validate treatment

**Researcher’s empirical cycle:**
- Analyze research problem
- Design research setup and inferences
- Validate
- Execute
- Analyse results

**Client’s engineering cycle:**
- Investigate client problem
- Design treatment
- Validate treatment
- Implement
- Evaluate
TAR methodology

Researcher’s design cycle:
• Investigate problem
• Design treatment
• Validate treatment

Researcher’s empirical cycle:
• Analyze research problem
  • Effects?
  • Satisfy requirements?
  • Comparison?
  • Generalizable?
• Design research setup and inferences
  • Acquire a case
• Validate
  • Internal validity?
  • External validity?
• Execute
  • Do the client cycle
• Analyse results
  • Answer questions.

Client’s engineering cycle:
• Investigate client problem
  • Stakeholders, goals?
  • Phenomena?
  • Causes, effects?
• Design treatment
  • Make a plan.
• Validate treatment
  • Check with client.
• Implement
  • Do it.
• Evaluate
  • Client satisfied?
Research Design

Research context

1. Knowledge goal
   – To validate a newly developed confidentiality risk assessment method

2. Improvement goal
   – To develop a confidentiality risk assessment method when IT is outsourced.

3. Current knowledge
   – The method has been tested on small problems in the lab
   – The method has been inspected by stakeholders of a client company
Research Design

Research problem

4. Conceptual framework
   – Concepts from outsourcing and security risk assessment

5. Knowledge questions
   • Q1 Is the technique usable?
   • Q2 Is it less subjective than other available techniques?
   • Q3 Does use of the technique improve the client’s understanding of confidentiality risks, better than competing techniques do?
   • Q4 Is the effectiveness of the techniques dependent on its context of use? If so, how?

6. Population
   – The set of all ERP outsourcing relations where the service consumer must satisfy confidentiality requirements checked by auditors and depends on the outsourcing service provider to satisfy these requirements.
Research design

Research & inference design

7. Object of study
   – large multinational industrial company with a significant corporate security staff keen on improving their procedures.

8. Treatment design
   – The RA method designed by the researcher was customized for the company.
   – Some software tools were used.
   – A schedule of interactions was agreed with the company.
Research design

**Research & inference design, continued**

9. **Measurement design**
   - Usability measured by effort (time) to use;
   - Subjectivity measured by number of questions in the method that require personal judgment;
   - Client’s understanding measured by debriefing interview
     - Data sources: Architects, Chief security officer, primary documents
     - Instruments: Diary of researcher, Interviews with key stakeholders
     - Measurement plan: Agreements about what data could be collected, and how
   - **Inference design: After the break!**
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Research & inference design
7. Object of study?
8. Treatment specification?
9. Measurement specification?
10. Inference?
Case-based inference design

Data → Description → Observations → Abduction (Explanation) → Explanations

Statistical induction → Generalizations → Analogy → Sample-based research

1. Describe
2. Statistically infer study population properties
3. Explain in terms of variables & causes
4. Generalize to theoretical population by architectural analogy

Sample-based research

1. Describe
2. Statistically infer study population properties
3. Explain in terms of variables & causes
4. Generalize to theoretical population by architectural analogy

Case-based research

1. Describe
2. Explain in terms of architecture & mechanisms
3. Generalize by architectural analogy
Case-based inference design

Case-based research
1. Describe
2. Explain in terms of architecture & mechanisms
3. Generalize by architectural analogy

Sample-based research
1. Describe
2. Statistically infer study population properties
3. Generalize to theoretical population by architectural analogy

Descriptive validity

Internal validity

External validity
Validity

• Validity is the degree of support for your inferences
  – It is not the degree of truth of your conclusions

• Validity discussion: discuss all of the possible ways in which your inferences could be wrong
  – Legal reasoning: your opponent will try to undercut all your arguments.
Sample—based inference design

Case-based research
1. Describe
2. Explain in terms of architecture & mechanisms
3. Generalize by architectural analogy

Sample-based research
1. Describe
2. Statistically infer study population properties
3. Explain in terms of causes, mechanisms, reasons
4. Generalize to theoretical population by architectural analogy
Sample—based inference design

Case-based research
1. Describe
2. Explain in terms of architecture & mechanisms
3. Generalize by architectural analogy

Statistical conclusion validity

Internal validity

External validity

Descriptive validity

Sample-based research
1. Describe
2. Statistically infer study population properties
3. Explain in terms of causes, mechanisms, reasons
4. Generalize to theoretical population by architectural analogy

Data → Description → Observations

Abduction (Explanation)

Statistical induction

Analogy

Explanations

Generalizations

Abduction (Explanation)
Descriptive inference design

• Descriptive inference
  i. Data preparation
     • Deal with missing data, outliers, perform transformations, etc.
  ii. Data interpretation
     • Conceptual analysis of text, images etc., content analysis, grounded theory, etc.
  iii. Summaries
     • Textual, numerical, graphical, qualitative.

• Descriptive validity
  – Triangulation (multiple sources, multiple interpretation methods, multiple coders)
  – Member checking: check with subjects
  – Peer debriefing: check with peers
Statistical inference design

• **Statistical inference**
  – There can be no statistical inference from a sample of one or more case studies
  – To use statistical inference in sample-based designs, check the assumptions of the statistical inference techniques.
Targets of generalization

- The study population is a subset of the theoretical population.
- What is the basis for generalizing to the theoretical population?
- Can we generalize numerical average and variance to the theoretical population?
Targets of generalization

- Case studies are about the analogies among the bullets
Abductive inference design

• **Abduction**
  – What possible explanations of case phenomena can you foresee?
    – Causes?
    – Mechanisms?
    – Reasons?

• **Internal validity**
  • What justifications of these explanations can you foresee?
  • Prior knowledge (common sense, scientific theories)
Analogic inference design

- **Generalization by analogy**
  - What is the scope of your explanation?
  - Similarity predicate of this class of cases? Shared architecture

- **Analytical induction**
  - Select a series of cases that you expect to confirm/disconfirm your generalization. If expectation is violated,
  - Redefine the similarity predicate to define away the problem or
  - Update the generalization to apply to all cases so far.

- **External validity**
  - Under which assumptions is the generalization justified?
Steps in sample-based research

• Define theoretical population (similarity predicate)
• Define study population (list of elements that serves as sampling frame)
• Define chance model
• Select sample
• Do measurements

1. Describe sample demographics & measurements
2. Statistically infer study population properties (test a hypothesis about, estimate confidence interval of, population parameter)
3. Explain in terms of causes, and explain causes in terms of mechanisms
4. Generalize to theoretical population by architectural analogy
Steps in case-based research

- Define theoretical population (similarity predicate)
- Select next case (analytical induction strategy)
- Do measurements
  1. Describe case architecture & measurements
  2. Explain in terms of architecture & mechanisms
  3. Generalize by architectural analogy
Inferences in example observational case study

An Empirical Study of the Complex Relationships between Requirements Engineering Processes and Other Processes that Lead to Payoffs in Productivity, Quality, and Risk Management

Daniela Damian and James Chisan
TSE 32(7) July 2006
A causal model presented in the paper.

Practioners’ opinions!

Researcher-observed practitioner-perceived correlations
The variables characterize the way of working of a cross-functional team, and its effects.
An architectural model constructed from the paper.

Mechanisms that explain improved productivity, quality, risk mgmt:

**C-F team**
- improves shared feature understanding,
- reduces rework

**C-C board**
- prevents requirement creep
Which inferences can we now support?

• **Abduction:**
  – *It is plausible that this architecture promotes these mechanisms, which contributed to the effect*
  – *Other mechanisms in this case that may have contributed to these effects:*
    • *New management may have impacted the effect variables as well*
    • *Other processes were changed too*
    • *The product was mature*

• **Generalization:**
  – *About 150 members, small teams, tech, project, product mgrs*
  – *Ineffective customer communication*

• Need analytical induction to say more
Example Technical Action Research (TAR) study

Inference as designed

- **Descriptive inference**
  - Diagrams and other work products of applying the method are to be presented

- **Abduction**
  - The production of the outcome (a risk assessment) is explained by the application of the method.
  - Treatment (the method) was applied correctly: documenting the method in advance and continuously referring to it during use
  - No other mechanism that could account for outcome
  - Other explanations: competence of the researcher who applied the method

- **Generalization**
  - Scope: Large organizations; Outsourcing; Significant security department; Obligation to show that company is in control of their information assets.
Inferences actually done

• *Descriptions of the sample of OoS*
  • Some of the produced diagrams are reported
  • A few notes from primary documents and interviews are reported.

• *Explanations*
  • All products of applying the method were produced as prescribed by the method; the reason is that the researcher is the author of the method and understands exactly what needs to be done.

• *Generalizations*
  – Assumptions about context that make the scope more specific:
    • Industrial organization, very cost-sensitive environment (they often take confidentiality risks in order to save money)
    • Other users would need proper tool support
Validity

- Research setup must be valid wrt planned inferences
- Inferences actually done must be valid wrt research setup
Validity of research setup

• Inference support
  – What inferences can be supported by this research setup?

• Repeatability
  – Can other researchers repeat this research?

• Ethics
  – Does the setup satisfy ethical norms? (informed consent, no harm, fairness, confidentiality etc.)
Validity of inferences

• See chapters 12 (descriptive inference), 14 (abductive inference), 15 (analogic inference)

• Summarized in checklist B, 
Outline

1. What is design science
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The rules of the game
The goal of empirical research is to develop, test or refine theories. We never start empty-handed.
Rules of the empirical research game

• **Rule of posterior knowledge**: Beliefs created by the research are present *after* execution of the research, and are absent before executing the research.
  
  – *E.g. formulating hypotheses after the fact, and reporting that you had them before*

• **Rule of prior ignorance**: Any beliefs present *before* doing the research may influence the outcome of the research.
  
  – *E.g. believing that the tested technique is better than its alternatives*

• If you violate these rules, you cheat yourself and your readers
Assignment

• Make a design of your research
  – Top level design cycle
  – An example empirical research design within this design cycle.

• Summarize on a flip-over

• Wieringa, R.J. (2014) *Design science methodology for information systems and software engineering*. Springer Verlag


